University of Stuttgart
Institute of Space Systems

5th International Space Debris Re-entry Workshop 2020

A simple but universal systematic ranking of quantitative material demisability from experimental findings

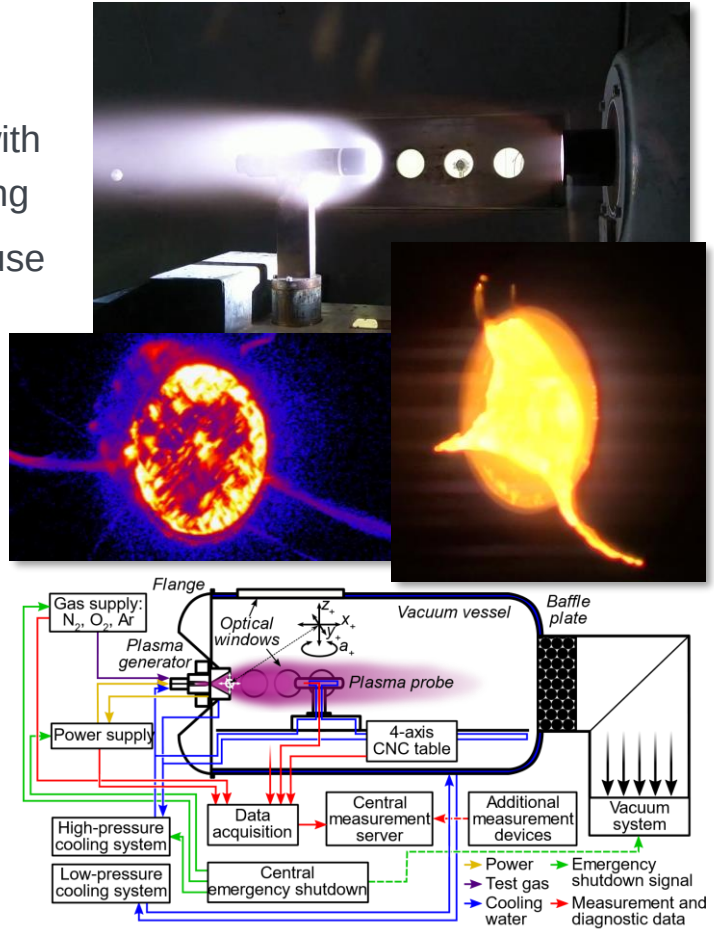
02 December 2020

Presenter: A.S. Pagan
Co-Author: G. Herdrich

Institute of Space Systems (IRS),
University of Stuttgart, Germany

Motivation

- **Objectives:**
  - Systematic quantitative comparison of distinct materials with varying demise phenomenologies subjected to PWT testing
  - Empirical refinement of heat of ablation material data for use with simple scaling models
- **Criteria:**
  - Universal applicability for effective comparison
  - Extractable from PWT testing
  - As simple (holistic) as possible, as complex (phenomenologically resolved) as necessary
- **Ideally reduction to two parameters:**
  - Effective heat of ablation/demise → Scaling
  - Threshold heating rate → Simple on/off criterion



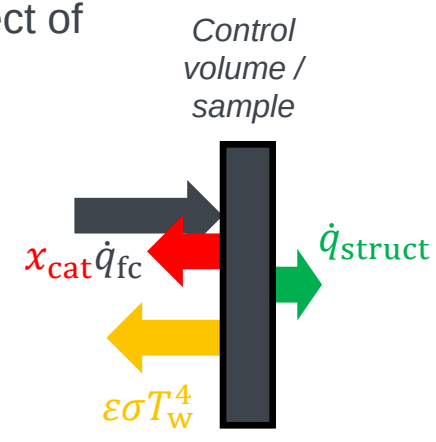
Procedure

Extraction of comparison metrics from PWT test data

1. Assess computation of heat of ablation / demise from experimental data for materials with distinct demise phenomenologies
2. Determine heat flux threshold for onset of demise from literature data and experiments (under consideration of catalysis where possible)
3. Approach empirical heat of ablation under consideration or neglect of
   - Catalysis, (phenomenologically reduced here, see also Ref. [1])
   - Re-radiation
   - Structural losses

   ➔ $\dot{q}_{\mathrm{eff}} \approx x_{\mathrm{cat}}\dot{q}_{\mathrm{fc}} - \varepsilon\sigma T_{\mathrm{w}}^4 - \dot{q}_{\mathrm{struct}}$

   utilising emissivity and catalysis correction data from dedicated experiments. Non-universal phenomena (e.g. convective blockage) included in effective heat of ablation / demise.

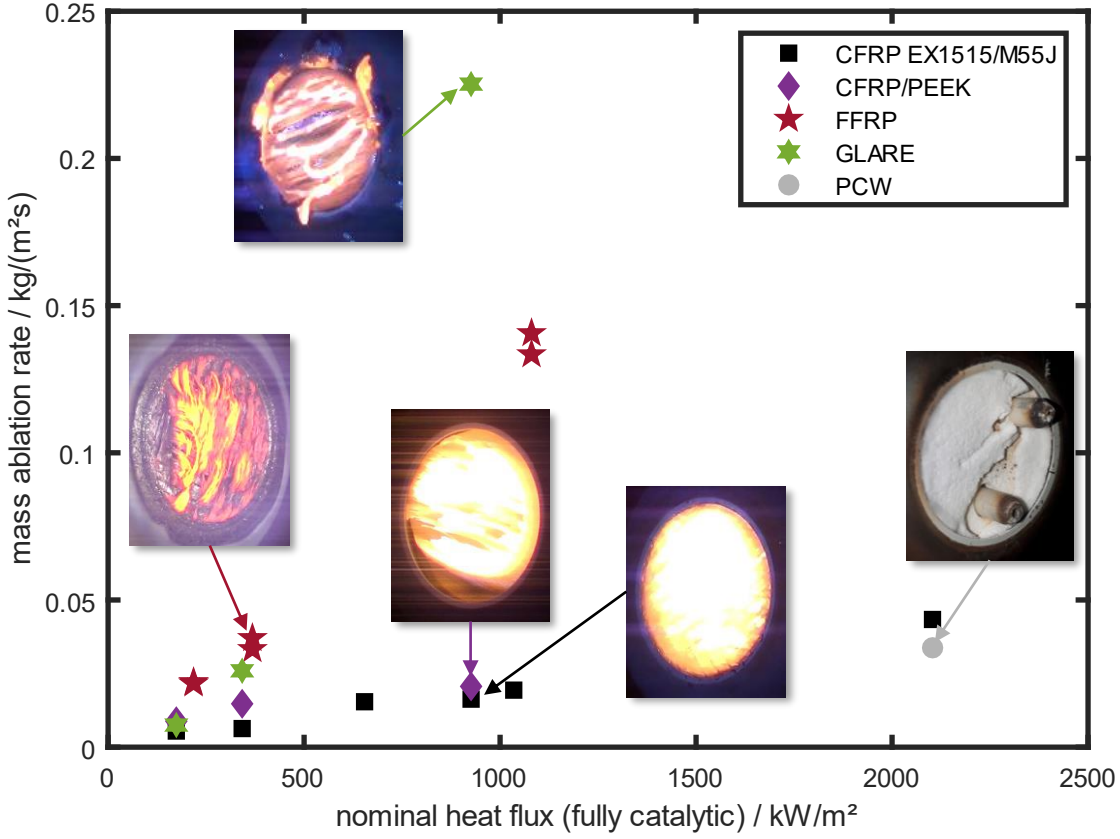


4. Obtain theoretical heat of ablation / specific enthalpy after melt for comparison

[1] B. Massuti-Ballester, G. Herdrich “Experimental Methodology to Assess Atomic Recombination on High-Temperature Materials”, *Journal of Thermophysics and Heat Transfer* 32(2), 2018, doi: https://doi.org/10.2514/1.T5132

Ablating Materials

Commonality: Mass loss rate scales with heat flux



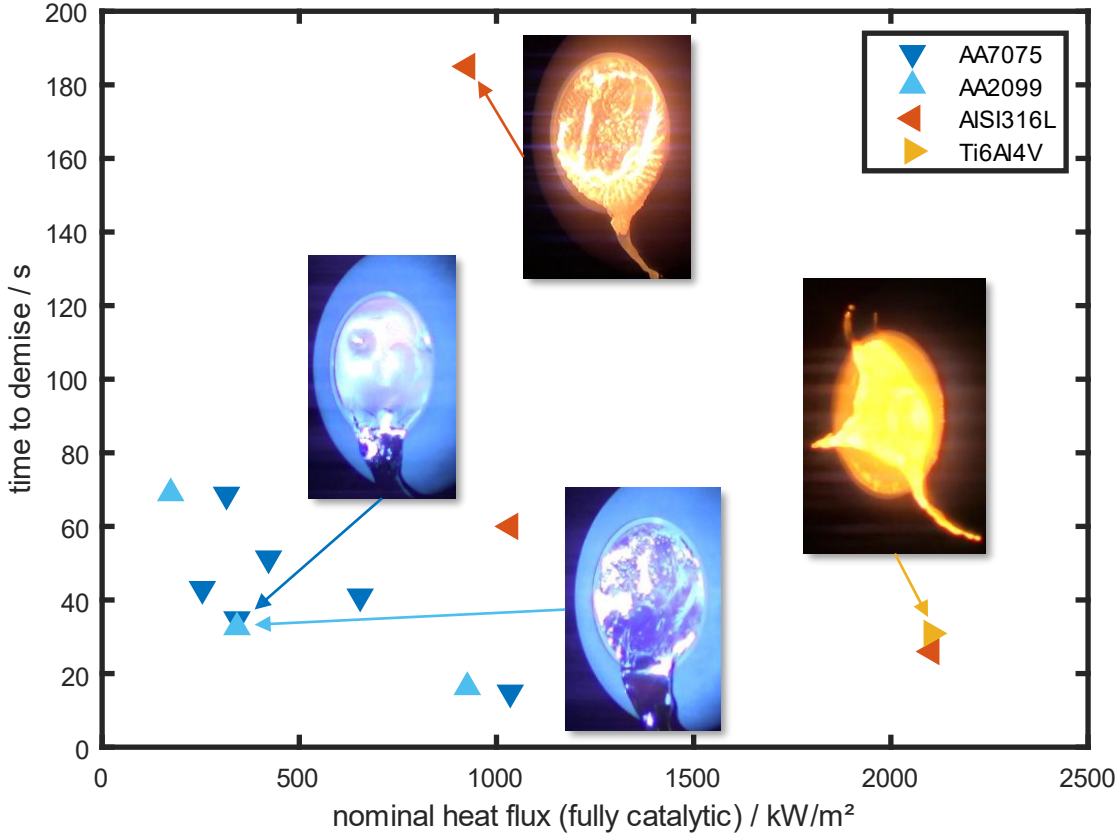
$$h_{\mathrm{abl}} = \frac{\dot{q}_{\mathrm{eff,lat}}}{\dot{m}_{\mathrm{abl}}}$$

Notes:

- "Cleanest" result for homogeneous linear behaviour
- Mass loss of single component (e.g. epoxy) may not suffice → two thresholds
- GLARE is a particularly „messy" material

Metals

Commonality: “Hard” melting temperature, non-scalable effects (e.g. oxide layer)



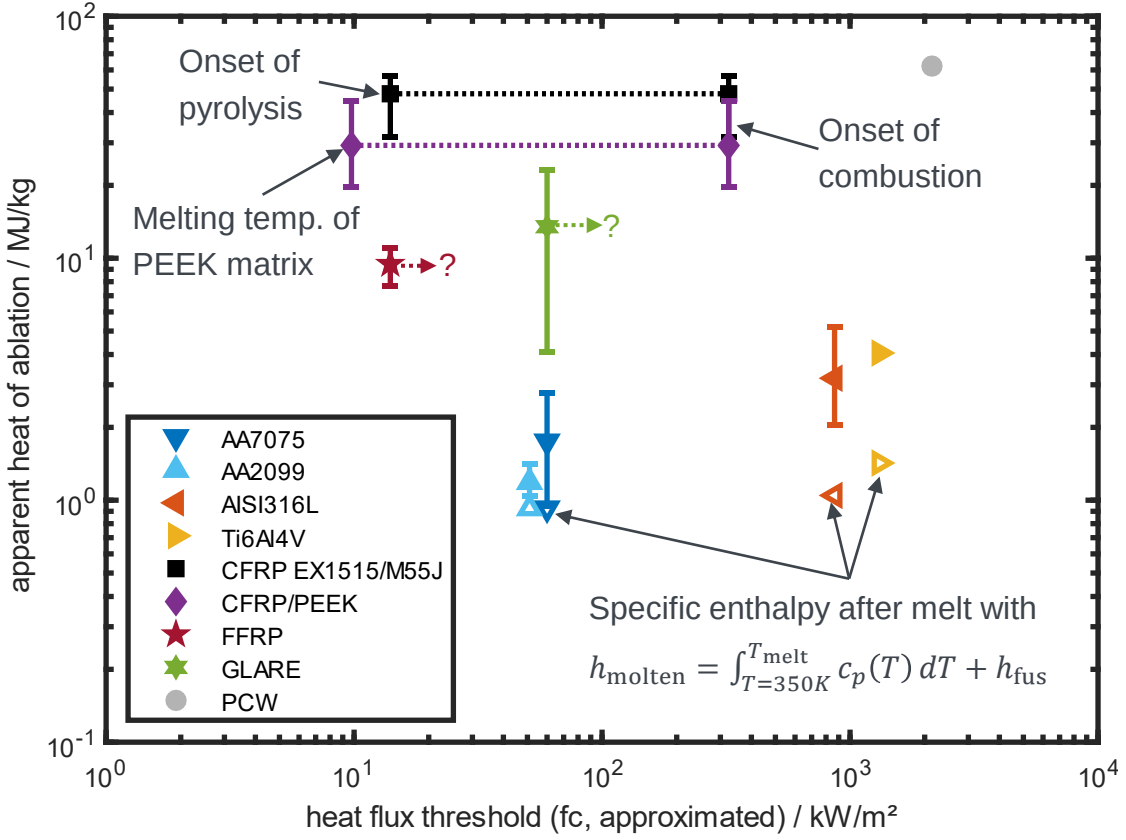
$$h_{\mathrm{abl}} = \frac{A \int_{t_0}^{t_{\mathrm{dem}}} \dot{q}_{\mathrm{eff}}\, dt}{\Delta m_{\mathrm{dem}}}$$

Notes:

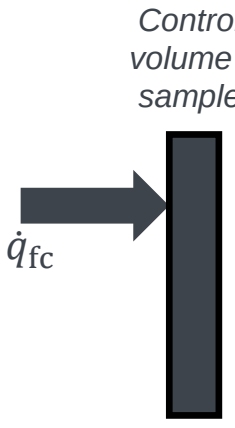
- Apparent timing of visible sample demise (significant outpouring of liquefied material)
- Somewhat arbitrary
  → uncertainty wrt melt of entire bulk mass
- “Cleanest” result if $t_{\mathrm{dem}} \propto \frac{1}{\dot{q}_{\mathrm{eff}}}$

Empirical Heat of Ablation/Demise vs. Heat Flux Threshold

No mitigation of heat flux considered → fully catalytic (fc)



$$\dot{q}_{\mathrm{eff}} \approx \dot{q}_{\mathrm{fc}}$$

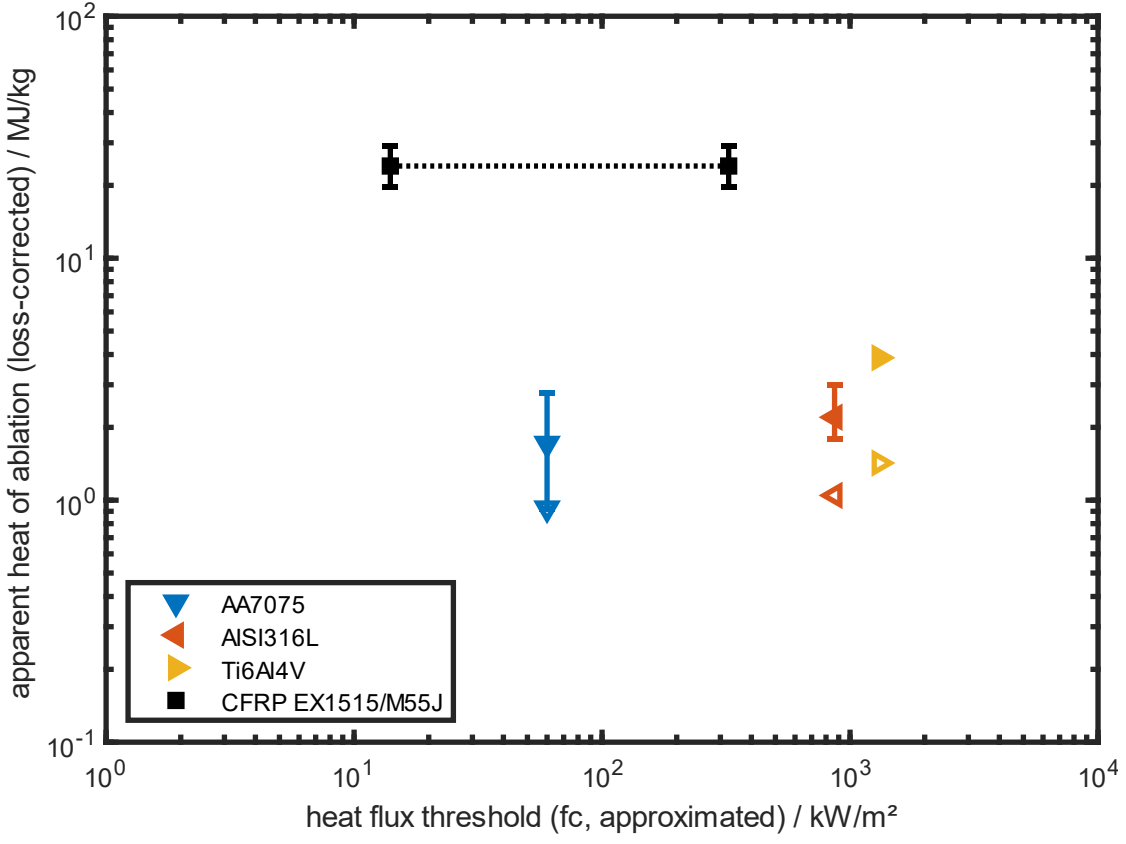


Note:

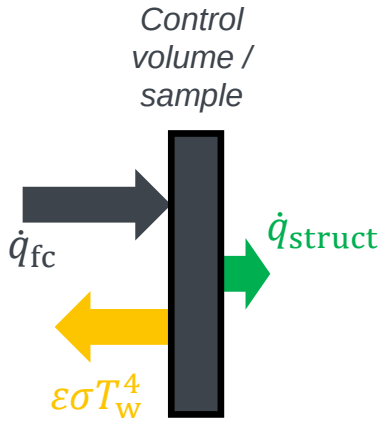
- Thresholds from radiance at critical temperature compensated for catalysis (experimentally / empirically assessed), structural losses neglected (context-dependent)

Empirical Heat of Ablation/Demise vs. Heat Flux Threshold

Subtraction of radiative (Stefan-Boltzmann) and structural heat losses (empirical)



$$\dot{q}_{\mathrm{eff}} \approx \dot{q}_{\mathrm{fc}} - \varepsilon\sigma T_{\mathrm{w}}^4 - \dot{q}_{\mathrm{struct}}$$



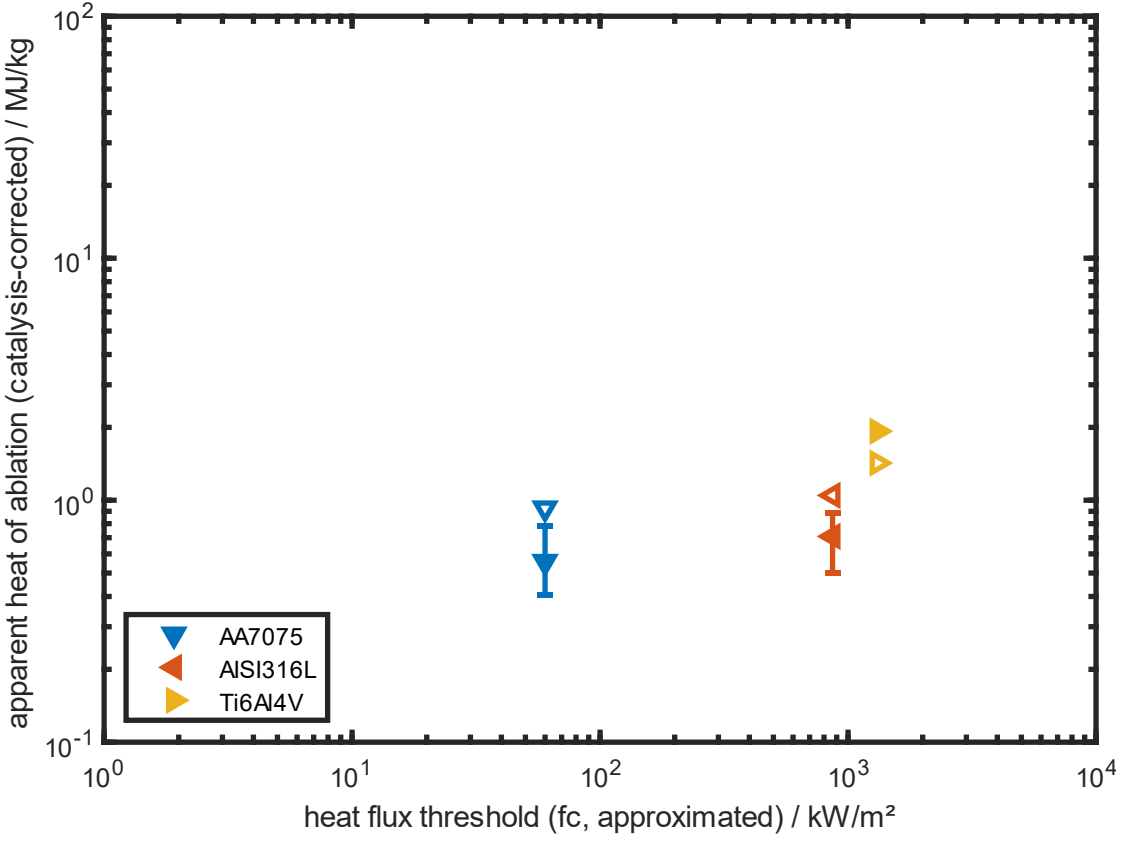
Note: Work in Progress!

➔ More materials tbd

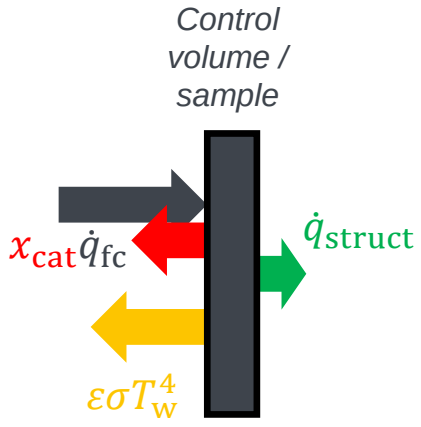
➔ Results are tentative

Empirical Heat of Ablation/Demise vs. Heat Flux Threshold

Catalysis correction determined (mostly) from steady state responses



$$\dot{q}_{\mathrm{eff}} \approx x_{\mathrm{cat}}\dot{q}_{\mathrm{fc}} - \varepsilon\sigma T_{\mathrm{w}}^4 - \dot{q}_{\mathrm{struct}}$$



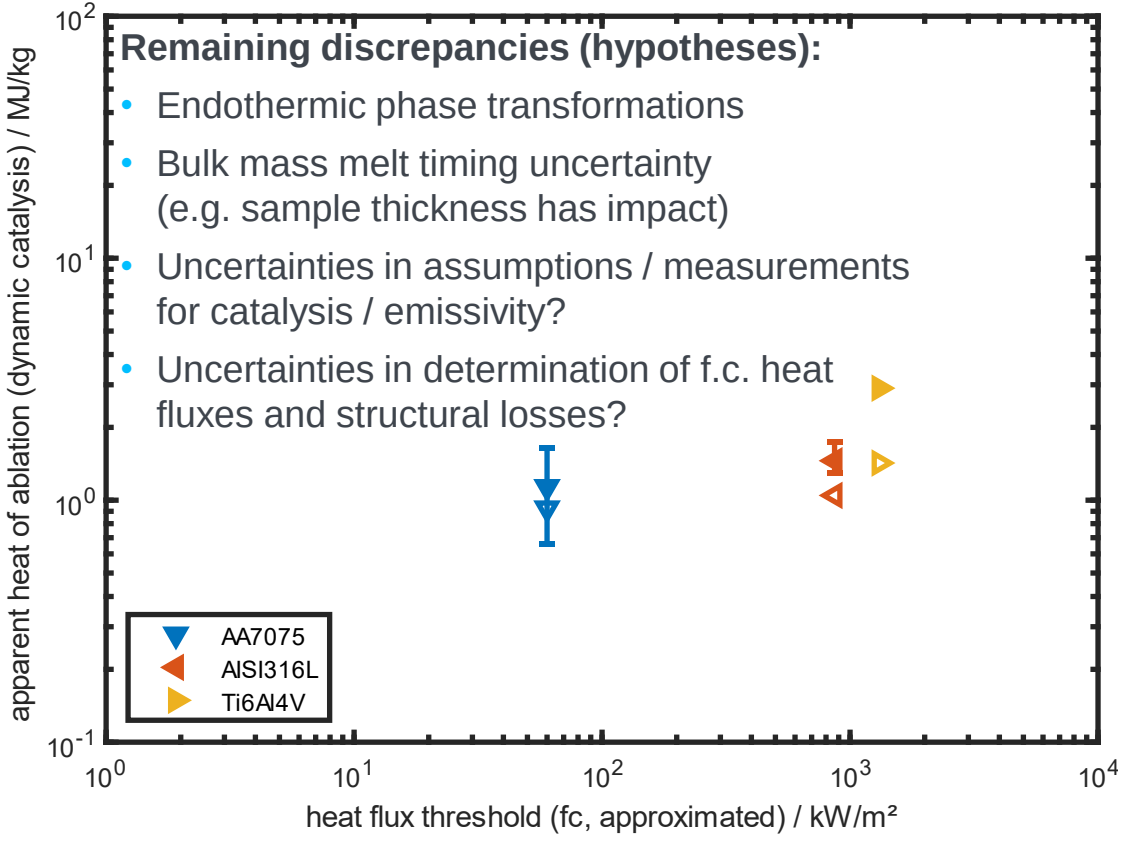
Note: Work in Progress!

➔ More materials tbd

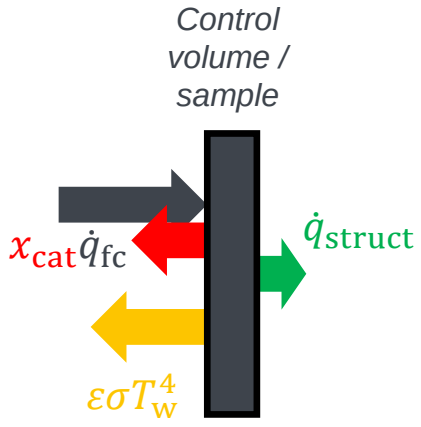
➔ Results are tentative

Empirical Heat of Ablation/Demise vs. Heat Flux Threshold

Assumption of wall-temperature-dependent “dynamic” catalysis



$$\dot{q}_{\mathrm{eff}} \approx x_{\mathrm{cat}}\dot{q}_{\mathrm{fc}} - \varepsilon\sigma T_{\mathrm{w}}^{4} - \dot{q}_{\mathrm{struct}}$$



Note: Work in Progress!

➔ More materials tbd

➔ Results are tentative

Conclusions

Summary

- Simple, straightforward and universally applicable comparison of material demisability from PWT test results
- Reduction to two key parameters (not new, really)
- Step-wise approach to theoretical heat of ablation with additional measurement data
  → Determine discrepancies of interest

Outlook / To Do List (Work in Progress!):

- Refinement / re-assessment of existing results
- Remaining materials to be added
- More extensive discussion of result implications (incl. non-scalable effects, e.g. spallation)
- Comparison with “proper” ablation models

University of Stuttgart
Institute of Space Systems

Thank you!

Dipl.-Ing. Adam S. Pagan

e-mail pagan@irs.uni-stuttgart.de
phone +49 (0) 711 685-62135
www. irs.uni-stuttgart.de

University of Stuttgart
Institute of Space Systems, Faculty 6
Pfaffenwaldring 29, 70569 Stuttgart

Acknowledgements

Most of the test data was obtained in the context of the following ESA-funded activities:

- **Characterisation of Demisable Materials**. Technical Research Program (TRP) primed by *Fluid Gravity Engineering Ltd.* (FGE, UK) under ESA contract no. 4000109981, conducted between 2014 and 2018.
- **Bio-demisable FFRP**. Material test campaign sub-contracted to IRS in context of TRP led by *Bcomp Ltd.* (Bcomp, CH) under ESA contract no. 4000122778, conducted in 2019.

Additional Plasma Wind Tunnel testing conducted in the framework of ongoing PhD thesis work.

Initial assessments for the presented findings were conducted in the context of:

- **Extension of the high-fidelity re-entry break-up simulation software based on new measurement types**. Technical Research Program (TRP) primed by *Hyperschall Technologie Göttingen GmbH* (HTG, DE) under ESA contract no. 4000126069, ongoing.